Critical Materials Institute

AN ENERGY INNOVATION HUB

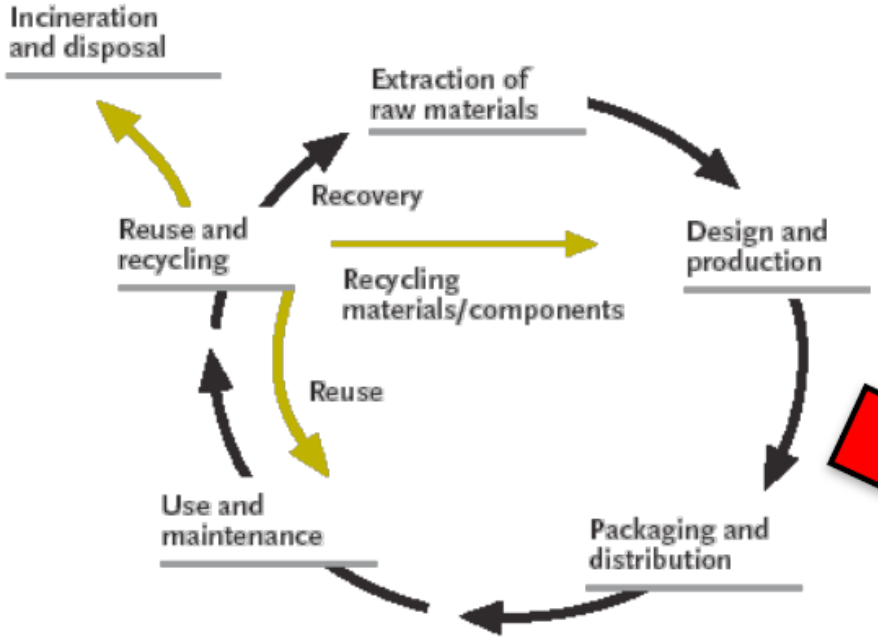
Cost Effective Hard Disk Drive Magnet Recovery & Reuse

Tim McIntyre

Grand Challenges

- **Creating New Rare Earth Sources**
  - How will China respond?
- **Understand the Economics of HDD Recycling**
  - Who has the HDDs?
  - How do I get'em?
- **Recover More, Recover Faster,…**
  - Process intact, crushed, shredded drives ➡ motors
  - 10 years ago ~10/hr., 4 years ago ~100/hr., NOW >1,000/hr..?
- **Reuse More, Reuse Better,…**
  - New HDDs from old HDDs – Seagate
  - New products with recovered components

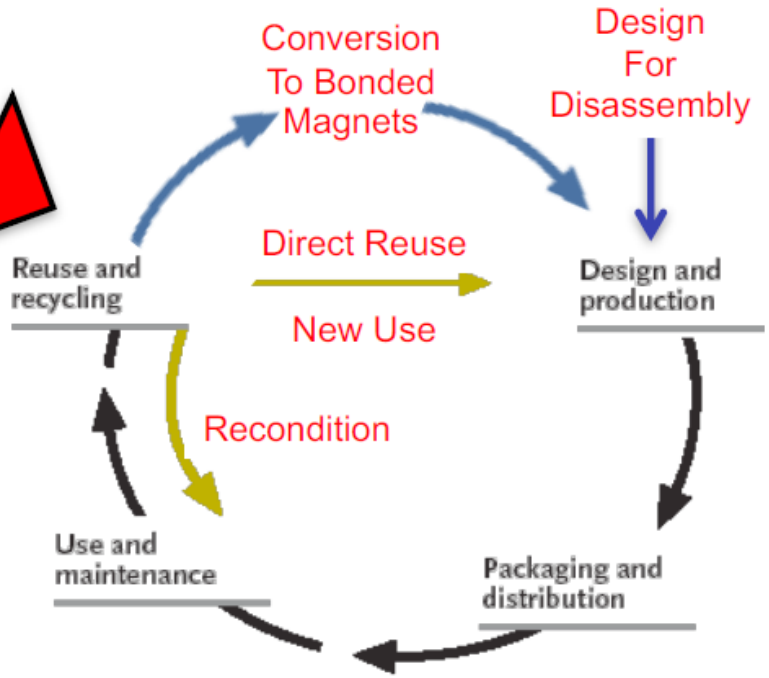
Closing the Loop on Circular Economy



FA3 Impact:

Stimulate new magnet reuse industry

- D*f*D for direct/new use – HiTech services
- High throughput recovery – services
- Conversion/recondition - manufacturing

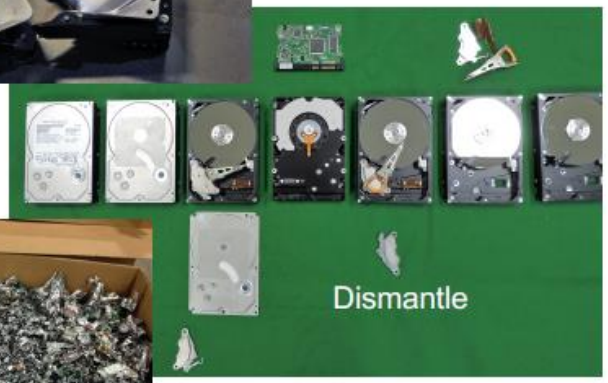


- Recycled hard disk drives alone will generate 600-760 metric tons per year of NdFeB
  - Significant alternate source
  - Stimulate new direct reuse manufacturing in the U.S.
- Substantial RE can be reclaimed from other end-of-life products – motors are next focus
- Disposal and diversion is eliminated

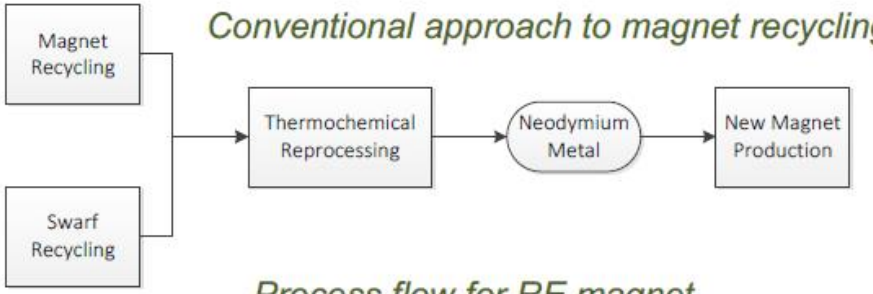
U.S. ships many recyclables overseas. They are processed and returned to the U.S. in consumer products over and over again.

Efficient Recovery at Scale

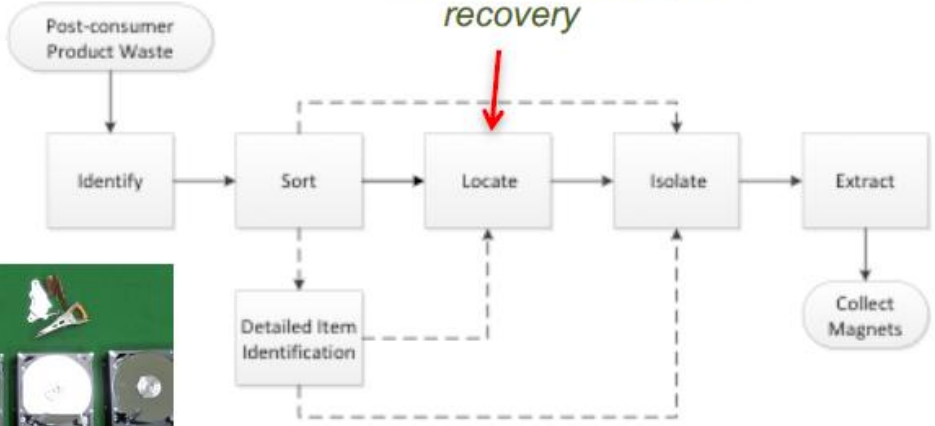
- **Develop functional requirements and design spec for magnet recovery**
- **Vet technologies for high speed processing**
- **Construct automated process**
- **Characterize performance limits and limitations**
- **Establish critical private sector partners**
- **Spin-up recycling enterprise**



Conventional approach to magnet recycling



Process flow for RE magnet recovery



Location system development revealed to us options for production-scale magnet recovery

Dismantle - Punch – Extract from Shreds

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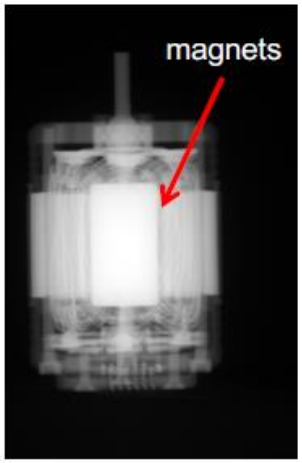
Locating Critical Features and Components

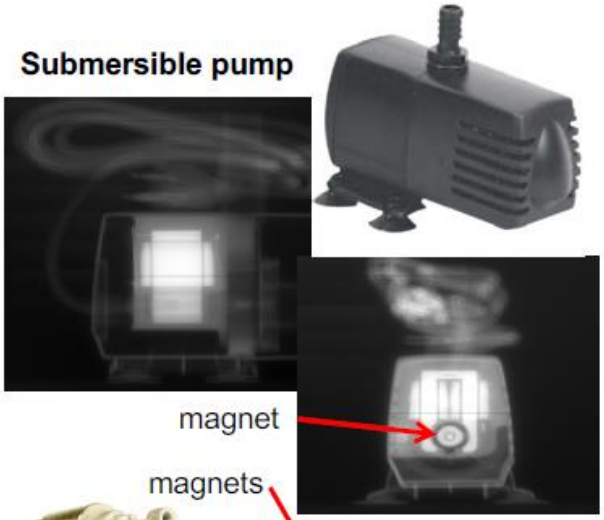
- X-ray radiography discerns features of interest.
  - Informs design of the HDD recovery system; motors, pumps, compressors?
  - Provides very high throughput location (up to 24,000HDDs/hr.) if needed
  - Capable of high resolution locating (0.4mm)

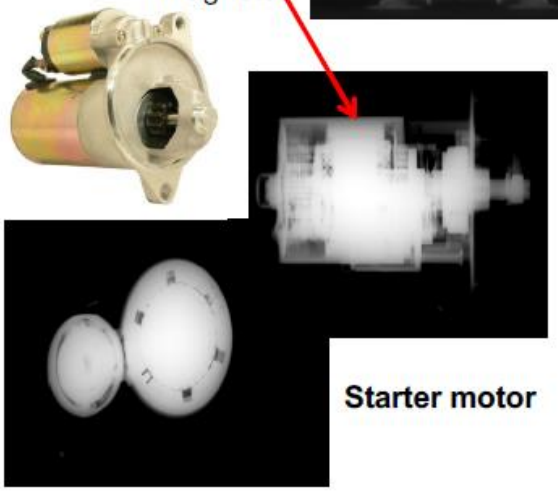
Hard disk drive

AC synchronous motor



Submersible pump





Starter motor

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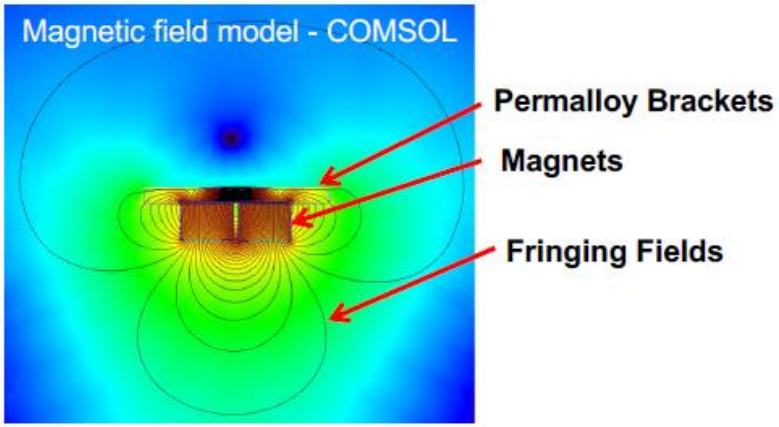
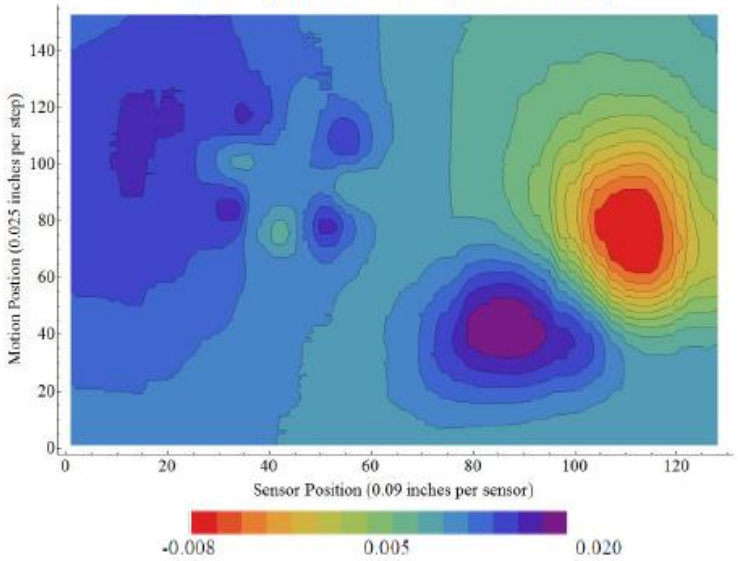
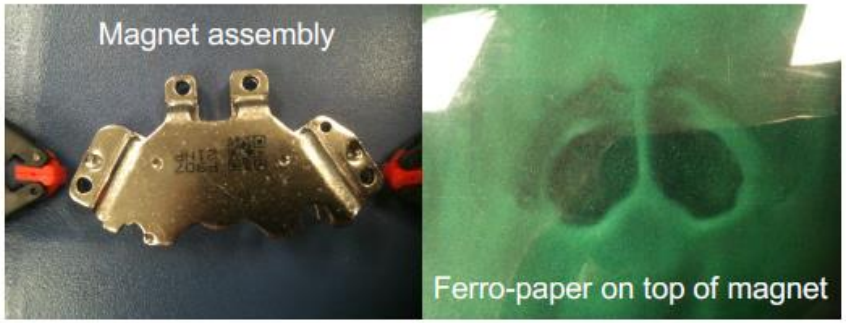
Locating Critical Features and Components

- Magnetic field imaging also discerns features of interest.
  - HDD design requires that fringing fields be kept at a minimum
  - Detailed feature extraction more challenging
  - Qualitative information good enough to locate magnet assembly

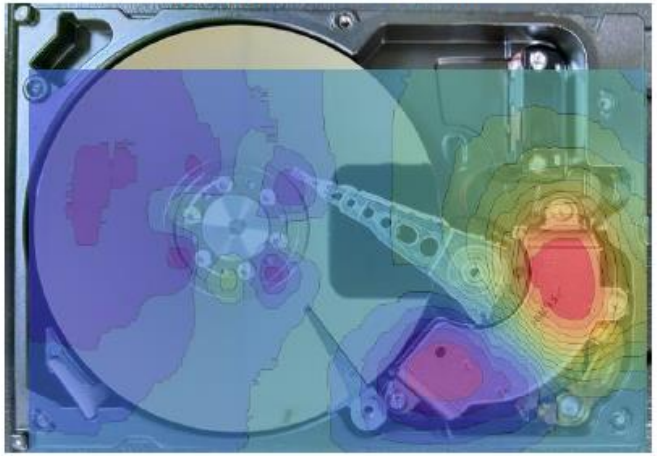


Magnetic field contour plot created by Hall Effect probe array



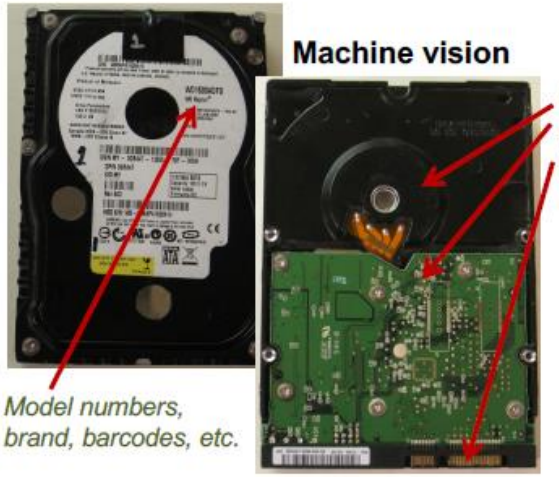


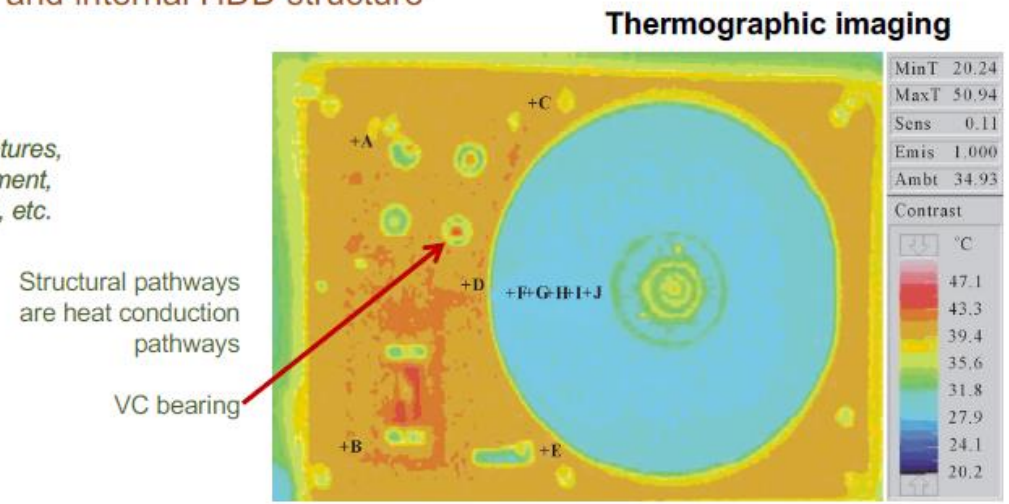
Contour plot overlay on HDD

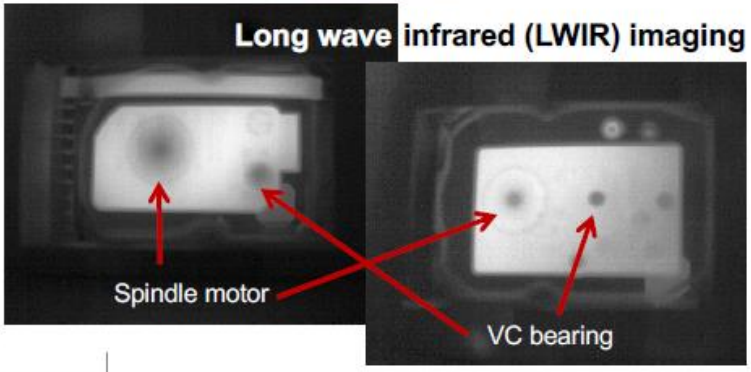


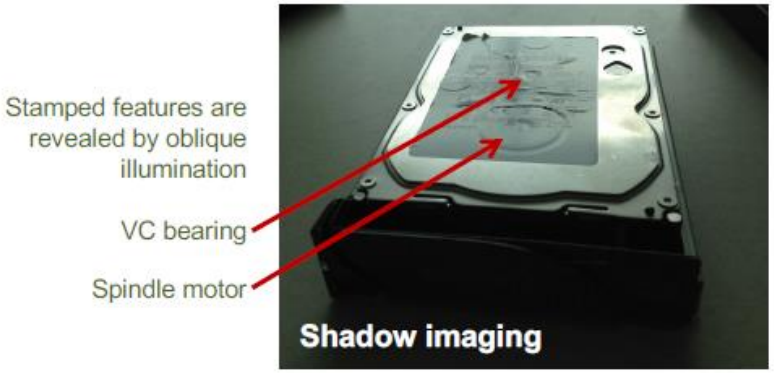
Locating Critical Features and Components

- Optical imaging also discerns features of interest.
  - Machine vision identifies and locates important shapes and patterns
  - Structured and tailored lighting enhances feature extraction
  - Infrared imaging reveals both external and internal HDD structure







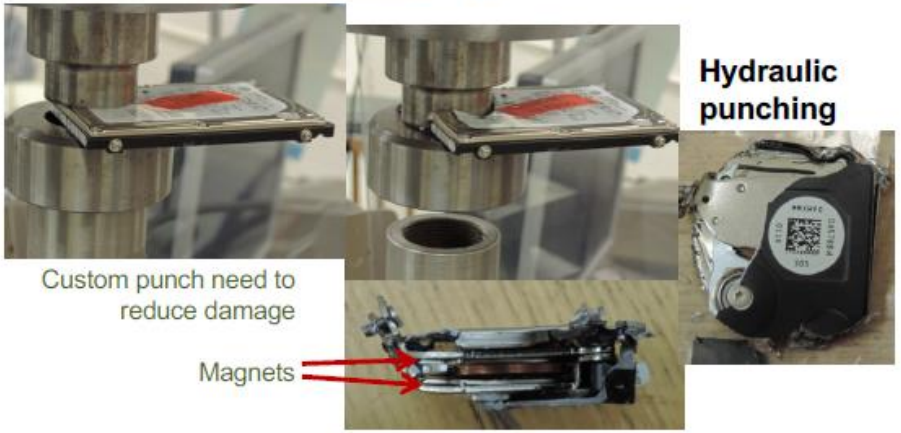


Rapid Magnet Assembly Extraction

- Several machining processes were evaluated.
  - Mechanical shearing rapidly separates (<1sec) the HD region containing the magnets, but is damaging
  - Water jet cutting is precise, but very slow (>30sec)
  - Mechanical punching is fast (<1sec), precise and may provide undamaged magnets

Mechanical shearing

Without a fixed stabilizing surface (die), the HDD is cut but severely damaged



Hydraulic punching

Custom punch need to reduce damage

Magnets

Other methods also attempted, including

- Sawing
- Electro-discharge machining (EDM)
- Plasma cutting

Multiple HDDs can be arranged for sequential cutting, reducing setup time

Magnets

Water jet cutting

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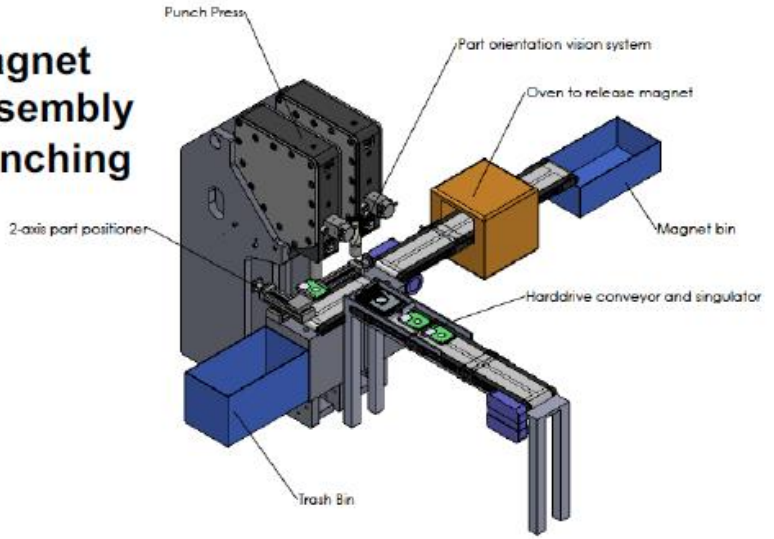
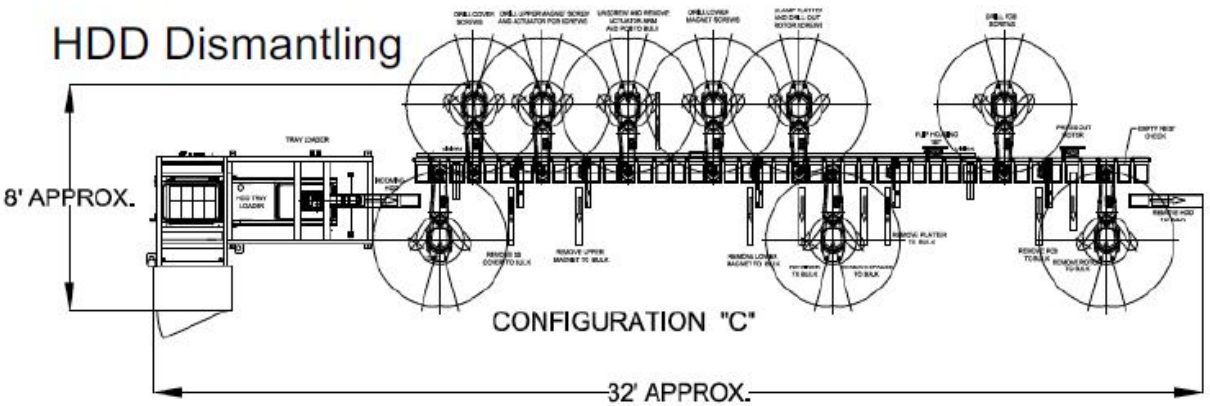
Integrated Mechatronic System Concepts

Magnet assembly punching



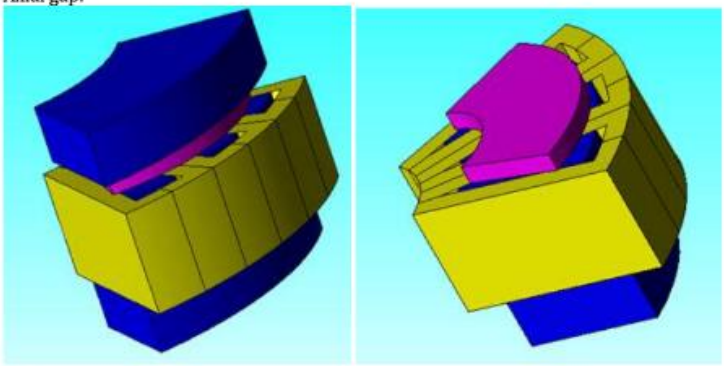
HDD Dismantling



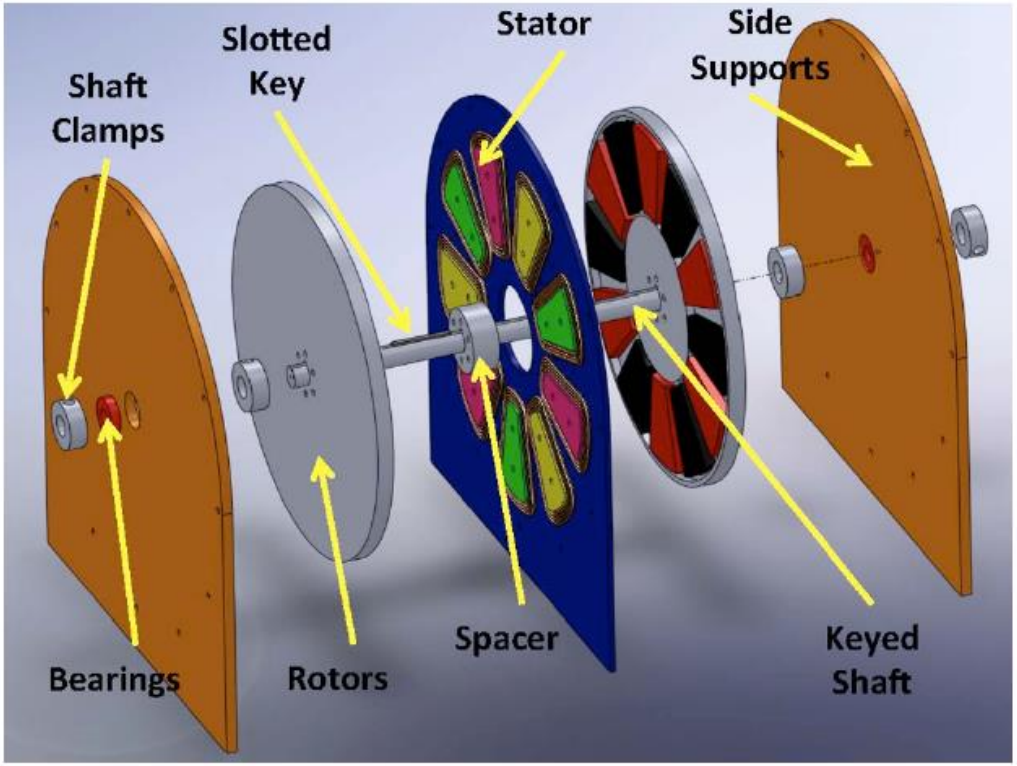
Direct Reuse of Materials or Components Maximizes the Value Proposition

Intact rare earth permanent magnets recovered from computer hard disk drives (HDDs).

Axial gap:



Magnet flux optimization model



Stator

Rotor

3-phase, dual-rotor axial gap traction drive motor (above); Axial gap rotor showing placement of recovered HDD magnets (left).

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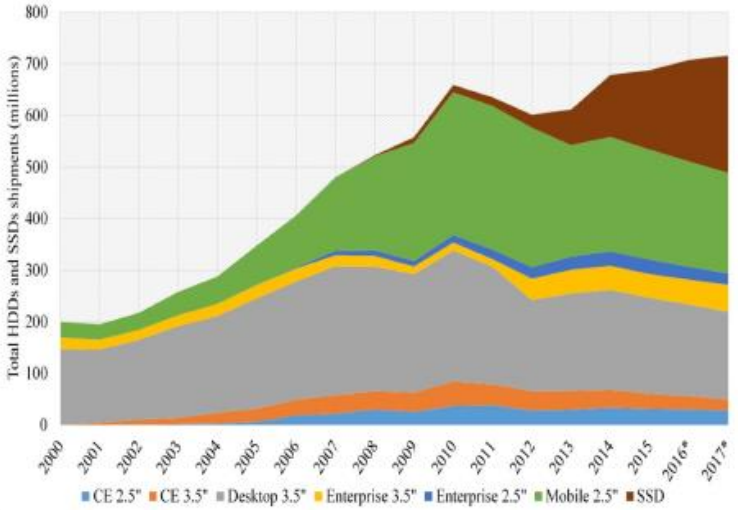
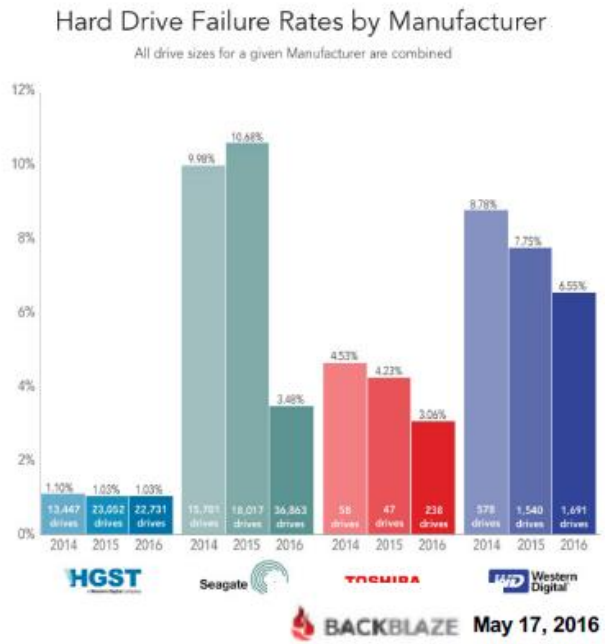
Creating New Rare Earth Sources

Creating New Rare Earth Sources

Computer Hard Disk Drives (HDDs)

- Large numbers
- Standardized form factor
- Market turnover





In general, data centers rotate their HDD stock every 5 years

Backblaze finds ~ 6% failure rate from "drive shopping" 2013-2015 HDDs

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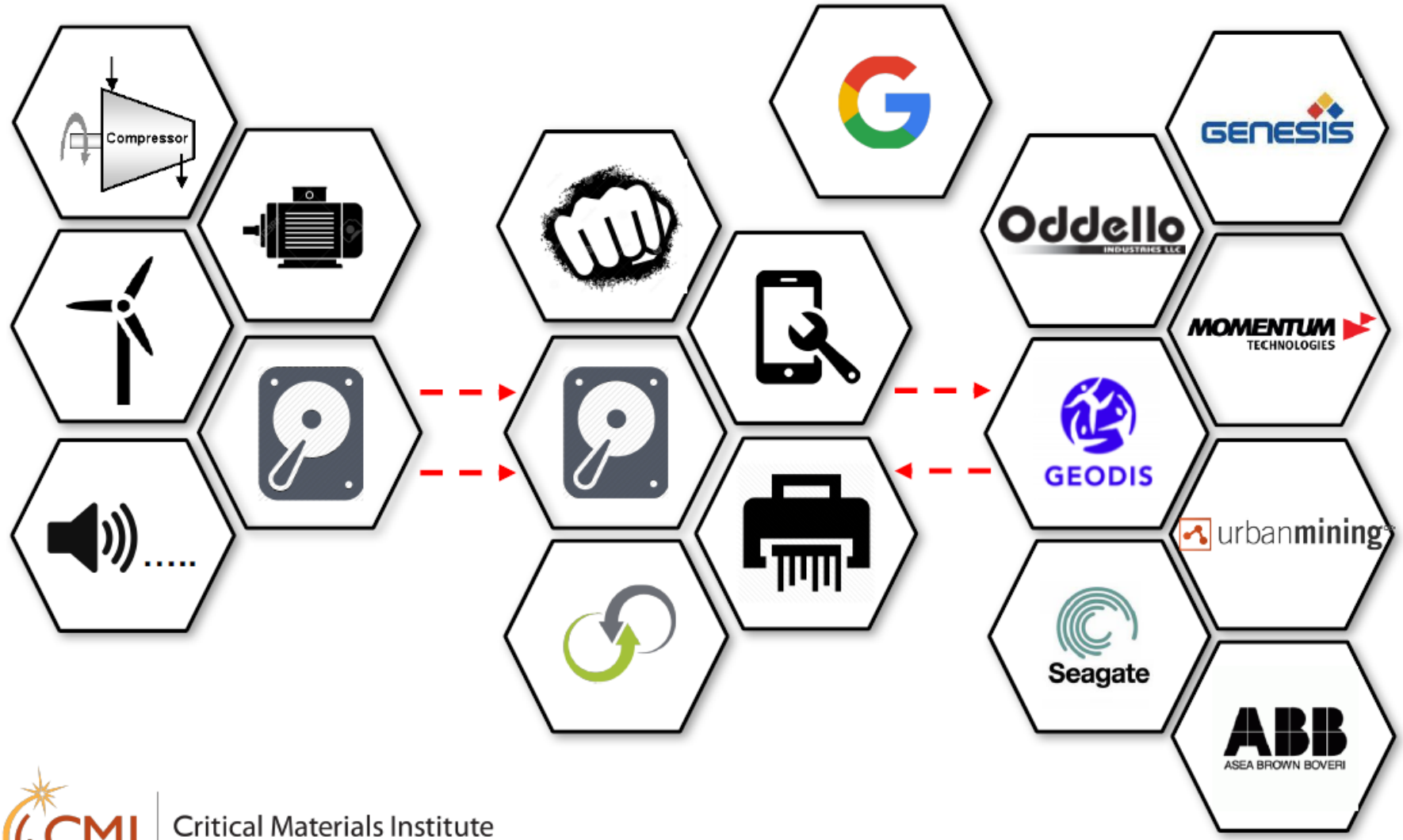
Creating New Rare Earth Sources

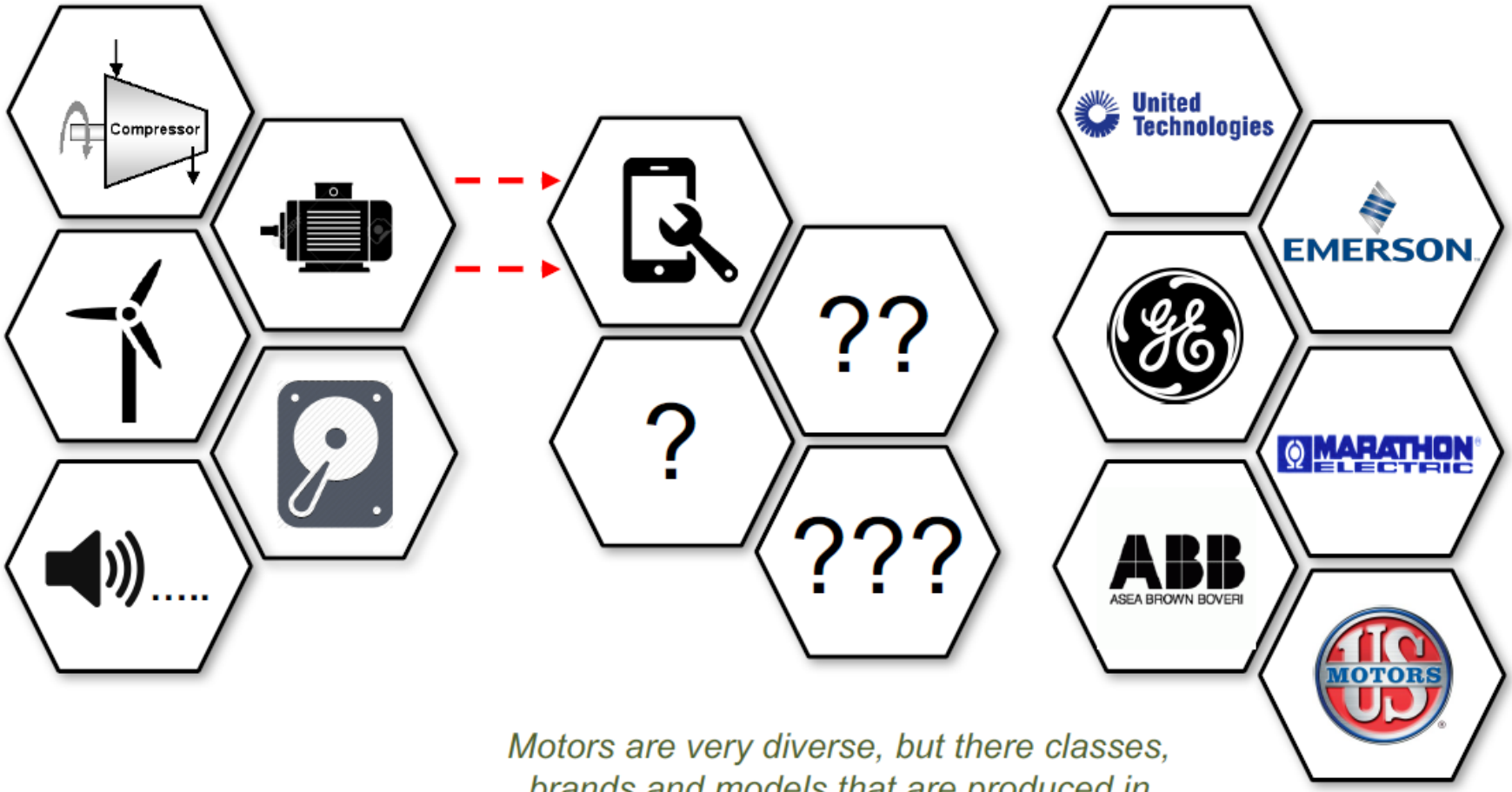


Creating New Rare Earth Sources

Products

Technology

Partnership+



Motors are very diverse, but there classes, brands and models that are produced in very large numbers.

Creating New Rare Earth Sources

Opportunities

- Partnering with private industry
  - Manufacturers, users, recyclers and re-manufacturers
- Engaging the public
  - Municipal recycling efforts
  - Policy makers at the local, state and federal level
  - Trade groups
  - News organizations

Challenges

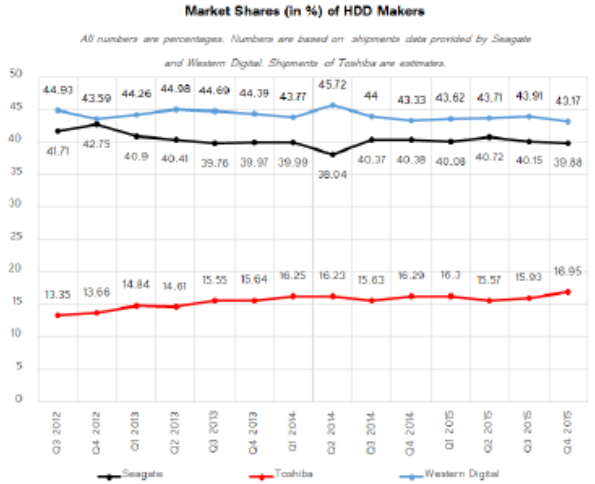
- Engagement
  - Make it easy
- Economics
  - Make $$$, early and often

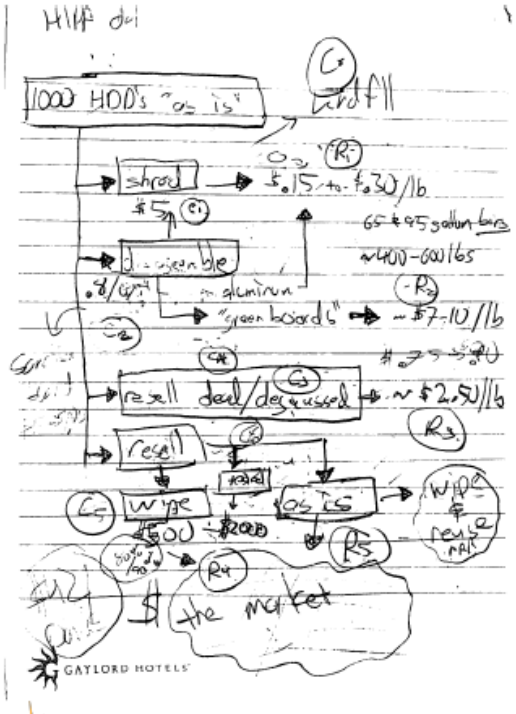
Understanding the Economics

Understanding the Economics

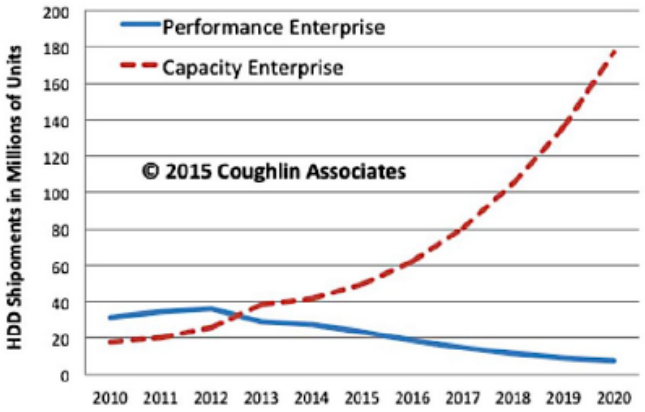
Recycled Value – Reuse Value

- iNEMI – value proposition analysis
- Teleplan reuse model
- Seagate's analysis by Bill Olson





Commodity	Customer Fees	Processing Costs	Sale Price	Overall Profit
Grade A Wiped $30/HDD Tradeloop	$0	-$500 to -$2,000 Wipe	+$30,000	= $28,000 to $29,500
Grade B Tested $20/HDD Tradeloop	$0	-$500 Test	+$20,000	= $19,500
Grade C Untested $15/HDD Tradeloop	$0	$0	+$15,000	= $15,000
Dead drives ~$2.50/lb Market Rate	$0	-$500 Degauss/Destruct	+$2,500	= $2,000
Dead drives, no boards $.15-$.30/lb Market Rate	$0	Disassemble	+$250	= $1,050
Green boards only $7-$10/lb Market Rate	$0	-$800 Disassemble	+$1,600	
Dead drives, shredded $.15-$.30/lb Market Rate	+$5,000	-$1,000 Shred	+$250	= $4,250



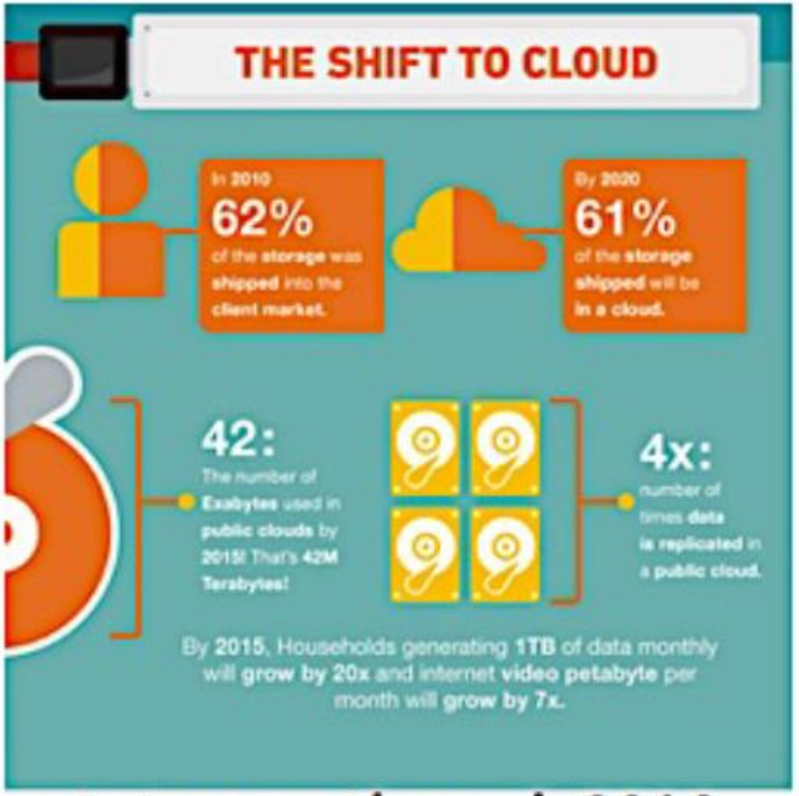
Resell HDDs = ~$9-29,000/1,000HDDs
Shredded mixed waste = ~$325/1,000HDDs
Shredded + PCBs = ~$800/1,000HDDs
Data secure/harvested ~$5,000++

Understanding the Economics

Seagate

The Demand for Storage Devices in a Connected World of Data

The TechNavio report Global Hard Disk Drive Market 2011-2015 predicted an 8.1% compound annual growth rate for the global HDD market through 2015.



COMPUTERWORLD

Hard disk drive shipments to soar through 2014

"Worldwide Hard Disk Drive 2010-2014 Forecast," estimates that hard disk drive purchases increased by 40.5 million in 2009, up to 52.6 million in 2014.

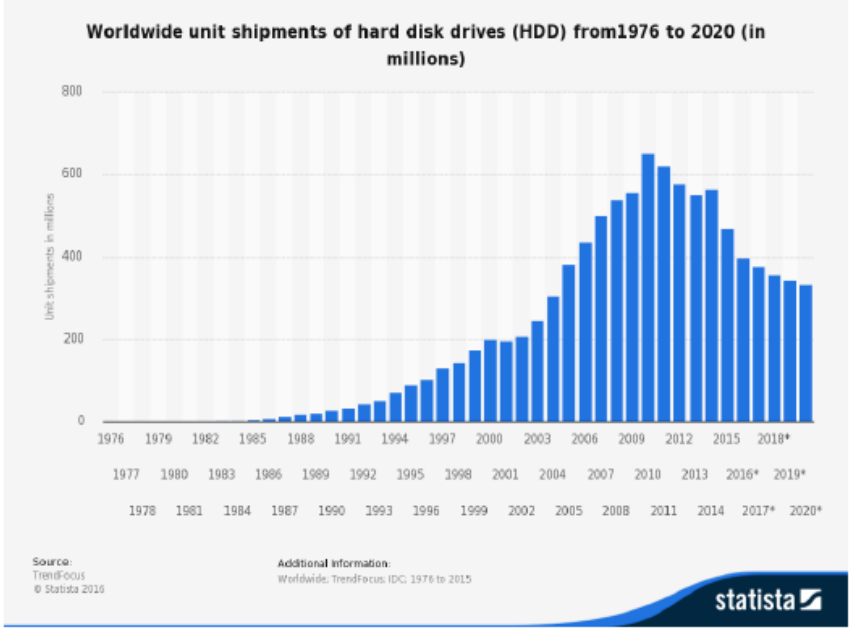
BY 2015, THE AVERAGE PUBLIC DATA CENTER WILL UTILIZE 42 EXABYTES OF DATA STORAGE
42,000,000 TERABYTES = 5,250,000 HDDS ASSUMING THE LUSTRE 8TB

Understanding the Economics – HDD census

- Trends Indicate Significant HDD Quantities Available for the Foreseeable Future

Consumer Class

- 10% to recyclers
- 30% to other e-waste stockpiles
- 20% to remanufacturer
- 40% not collected/shredded/landfilled

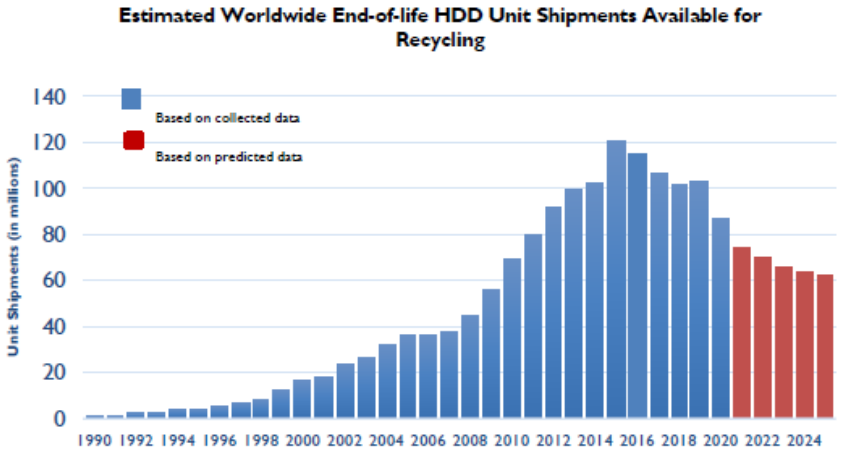


- FA4.3.2 estimates indicate the following disposition for End-of-Life HDDs

Imholte, et al., CMI, 2016

Enterprise Class

- 25% to recyclers
- 10% to other e-waste stockpiles
- 60% to remanufacturer
- 5% not collected/shredded/landfilled



Total HDDs shipped world wide to date = ~6.9 billion
Total projected shipped through 2020 = ~8.3 billion
Projected available for recycle (2016-25) = ~849 million
Total available per above criteria = ~60% = ~509 million
Total from E-Class only (35% of 50%) = ~149 million

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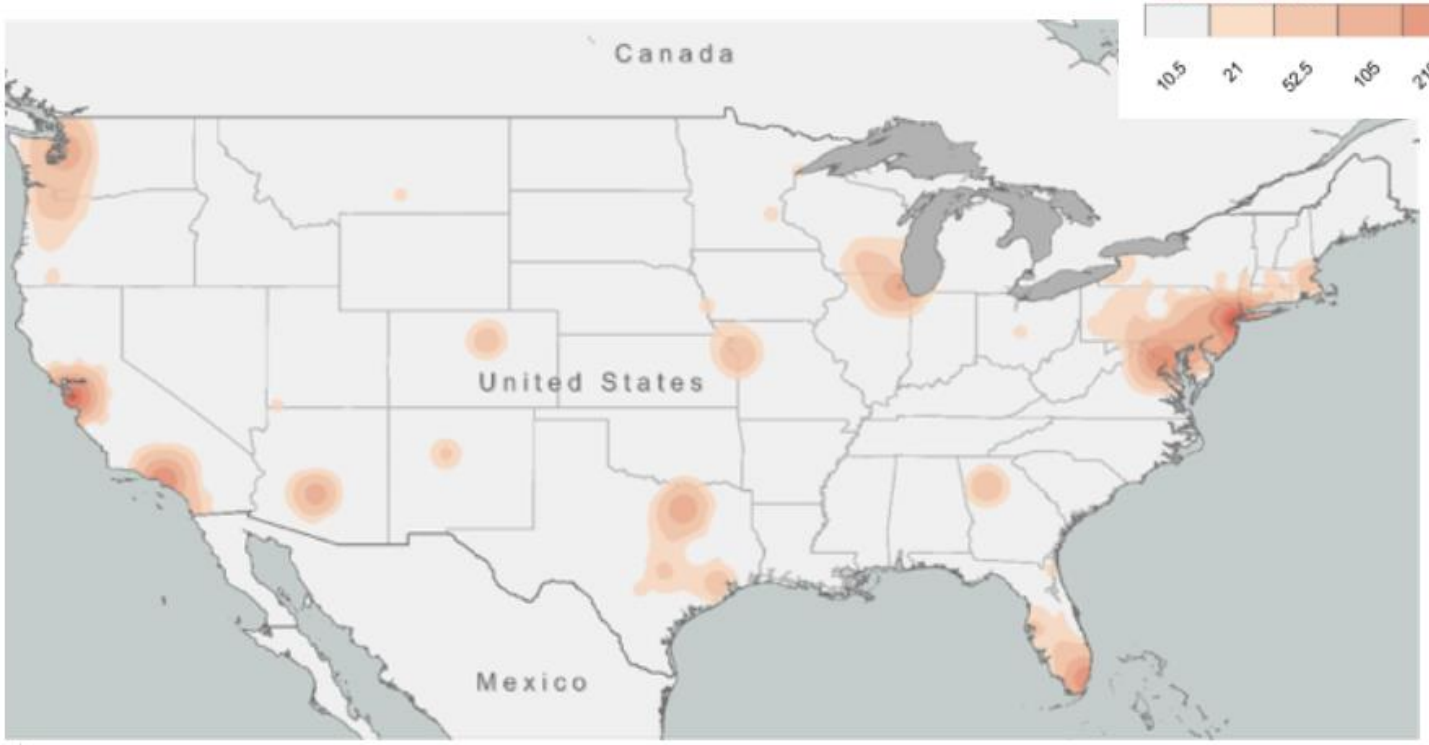
Understanding the Economics – HDD Geography

- This "heat map" shows clustering of internet exchange (IX) data centers
- Typical IX data center uses 600,000 HDDs



There are 5-9 large clusters of IXDCs

Corporate Enterprise DCs will augment these numbers

Imholte, et al., CMI, 2016

Recover More, Recover Faster,…

Creating New Rare Earth Sources - Punching

- Punching provides extremely rapid (1 HDD/sec) separation of the magnet assembly region of the HDD
- Custom punch design can be very effective for large quantities of similar HDDs

Punch & Die Set

Hydraulic Punch Press

Punch & Die Set

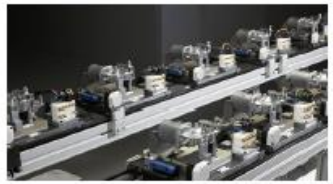
Observations

- Steel lid follows punch shape
- Aluminum case fractures at magnet assembly
- Magnet assembly intact
- Magnets damaged may be by VC arm during punching

Punched Magnet Assembly

Creating New Rare Earth Sources - Dismantling

- Ultra-high speed (>350mm/sec) robotic end mill technology used to remove fasteners
- Multi-output streams recovered undamaged
- Multi-reuse applications are enabled



- **~1 HDD processed every 4 seconds**
- **HDDs are singulated, aligned then dismantled**
- **HDD components recovered undamaged - Reuse**

First HDD direct reuse experiment by Seagate – Can we reuse the magnet assembly?

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Creating New Rare Earth Sources - Shredding

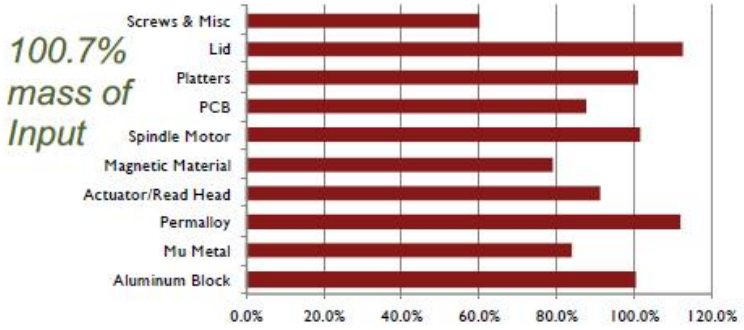
- Perceived as most data secure method of HDD recycling
- Also perceived as diminishing ability to recover maximum value ➡ send shredded material to metal recycler
- Most widely adopted HDD recycling method

Magnet hairball

NdFeB recovered from shreds

Discussions ongoing with HDD shredder companies

The output from "general purpose" shredder unpredictable

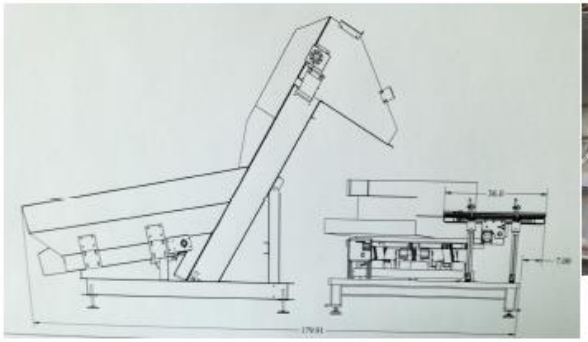


Major Challenges

Who are these guys?
Where are these guys?

- **Availability**
  - Tap into large sources of hard disk drives (HDDs)
  - Get the word out
- **Effficiency**
  - Manual disassembly, 8/hr, Hitachi, 2006
  - Tumble & prange, 100/hr, Hitachi, 2012
  - Punching, >1,000/hr, CMI, 2014
- **Working smarter**
  - Rapid robotic disassembly, ~1,000/hr, 2016

VC pivot drift



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Reuse More, Recover Better,…

Reuse – A Better Option?

- New HDDs from old HDDs
  - Seagate sending 5,000 HDD to ORNL for testing
  - They want to do experiments – looking at reusing magnet assemblies
  - Swop-out data platters, change the VC, reprogram?
- Motors from old HDDs
  - Several companies showing some interest
  - They also want to do experiments on different motor designs
- New products from old HDDs
  - 3D printing polymer bonded magnets - FDM
  - Printing miniature motors, RF electronics, sensors, etc. – Aerosol Jet printing
  - Magneto-caloric refrigeration???

Thank You!

Questions?

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